DEPARTMENT OF COMMERCE

UNITED STATES BUREAU OF MINES
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LIMESTONE

PART I - GENERAL INFORMATION

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I.C. 6723
June, 1933.

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DEPARTMENT OF COMMERCE - BUREAU OF MINES

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By Oliver Bowles[2] and D. M. Banks[3]

CONTENTS

	Page
Introduction	2
Description	2
Production by States	3
Branches of the industry	5
Dimension stone	7
Crushed and pulverized limestone	7
Extent of the industry	7
Uses	8
Uses for which physical properties are most important	8
Uses for which chemical properties are most important	11
Uses of dolomite and high-magnesian limestone	15
Quarry methods	15
Underground mining	19
Preparation of materials	19
Operating costs	20
Markets	21
Prices	21
Royalties	21
Capital requirements	21

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INTRODUCTION

Limestone is the most widely used of all rocks and is essential to a great many industries, including the building trades, highway construction, metallurgy, agriculture, and many chemical and manufacturing enterprises. It occurs in some form in every State and is produced in thousands of quarries. Production in 1930 exceeded 134,000,000 tons. It has more numerous and more diversified uses than any other rock.

This paper is designed to furnish general information on the various branches of limestone quarrying and their economic importance. Brief reference is made to dimension stone, and a more complete discussion follows of the uses, requisite qualities, quarry methods, and processes of preparation of crushed and broken limestone. Footnote references serve to guide the reader to more detailed information.

DESCRIPTION

Limestone is composed ordinarily of calcareous shells of ancient sea animals. It was formed in beds on the sea floor by the accumulation of such shells, together with varying quantities of other substances such as magnesium carbonate, silica, clayey material, salts of iron, and organic matter; and by pressure the entire mass was gradually consolidated into rock. Through long geologic ages of surface adjustment these formations came to occupy land areas and so became available for commercial use.

The essential constitutent of limestone, therefore, is calcium carbonate ($CaCO_3$), and many commercial limestones consist almost entirely of this material. Such rocks are designated commercially as high-calcium limestones. When other substances occur in the stone, classification is made according to the nature of the impurities. For instance, if 10 per cent or more of magnesium carbonate is present, it is called "magnesian" or "dolomitic" limestone; when the amount approaches 45 per cent, the rock is known as dolomite, which is the double carbonate of calcium and magnesium expressed by the formula $CaCO_3 . MgCO_3$. Other varieties are "siliceous" or "cherty" limestones, which contain considerable silica; "argillaceous," containing clay or shale; "ferruginous," of considerable iron content, which usually gives the rock a buff, reddish, or yellowish color; "carbonaceous" or "bituminous," in which carbonaceous matter, such as peat or other organic materials, is present and gives to the rock a dark gray or black color.

Some limestone beds have been formed under conditions that have left many shells almost intact or, at least, in fragments sufficiently well preserved to indicate their origin and character. These are known as "fossiliferous" limestones. Some of them are made up almost entirely of shells of one kind and are named accordingly. "Coral," "crinoid," and "coquina" are common types; "chalk" is a fine-grained, white, friable limestone which is composed largely of minute shells of foraminifera; oyster-shell beds are quite extensive.

Two varieties of limestone, travertine and Mexican onyx, consist of calcium carbonate that has been deposited from solution. The first is a product of chemical precipitation from hot springs. It is deposited in successive layers, and as chemical composition and conditions of deposition may vary during this process a banded structure commonly results. The rock is characterized by numerous irregular cavities. The second type, Mexican or cave onyx, is deposited from cold-water solutions in limestone caves. It is to be distinguished from true onyx, which consists of silica. As Mexican onyx is susceptible of polish it is classed with marbles rather than with limestones.

Another series of names is applied to limestones according to their physical character. "Common compact" is the most widespread type; it consists of a fine-grained, dense, homogeneous aggregate varying in color from light grey to almost black. "Lithographic" is an extremely fine-grained crystalline variety, usually of drab or yellowish color. "Oolitic" limestone is made up of small, rounded grains of lime carbonate with a concentrically laminated structure.

PRODUCTION BY STATES

Deposits of limestone occur in every State. Stone suitable for building is quarried in about half of them, but most of the output originates in Indiana. Quarries for production of crushed or pulverized limestone are very widely distributed; in some States hundreds of them are in operation. While building stone production is a long-established industry, the manufacture of crushed stone has within the past 50 years grown from a small and insignificant industry to one that attained in 1929 a volume of approximately 151,000,000 tons a year. The production (sales) of limestone by States for 3 years is shown in table 1.

Table 1.- Limestone sold or used by producers in the United States, 1929-1931, by States[1]

(Quantities approximate)

State	1929		1930		1931	
	Short tons	Value	Short tons	Value	Short tons	Value
Alabama	1,190,770	$1,771,201	905,760	$1,537,680	514,290	$1,406,[illegible]
Arizona	162,020	147,619	75,390	61,417	31,780	31,502
Arkansas	132,760	170,287	314,250	373,059	87,250	101,435
California ...	261,280	653,681	296,180	587,387	240,180	549,792
Colorado	438,980	458,983	332,310	324,851	233,780	293,660
Connecticut ..	37,030	112,891	35,210	103,359	37,270	95,901
Florida	2,258,130	1,669,245	1,796,670	1,490,173	1,359,460	1,219,214
Georgia	401,320	488,700	315,850	378,060	746,710	658,544
Hawaii	2,670	9,352	2,720	9,108	970	3,454
Idaho	29,820	70,623	19,320	25,099	7,820	14,890
Illinois	8,345,080	6,965,264	7,538,810	5,909,089	5,278,170	3,945,064
Indiana	5,129,220	22,191,883	4,515,460	19,245,409	2,831,910	10,257,555
Iowa	1,624,400	1,549,743	1,813,860	1,850,823	1,271,310	1,208,755
Kansas	1,392,230	1,413,146	1,248,670	1,245,088	1,099,400	1,035,663
Kentucky	2,443,880	2,558,068	2,625,080	2,602,022	2,179,530	1,897,793
Louisiana	(2)	(2)	(2)	(2)	(2)	(2)
Maine	83,980	130,125	101,950	128,892	57,590	82,953
Maryland	346,810	470,246	549,320	723,065	509,180	566,495
Massachusetts.	83,930	303,795	78,730	276,501	69,480	255,080
Michigan	13,572,010	8,425,261	10,432,950	6,596,713	6,059,770	3,805,607
Minnesota	280,690	830,122	300,000	840,860	284,960	816,484
Mississippi ..	(2)	(2)	(2)	(2)	(2)	(2)
Missouri	4,093,430	5,704,241	3,654,920	4,819,475	3,350,660	3,962,46
Montana	134,490	140,164	94,050	114,819	78,740	97,454
Nebraska	178,200	335,789	103,120	188,674	74,030	117,51
Nevada	33,400	51,805	30,120	46,850	(2)	(2)
New Jersey ...	166,750	368,504	176,920	386,451	137,820	329,45
New Mexico ...	(2)	(2)	(2)	(2)	195,550	380,44
New York	11,105,850	13,841,827	11,185,920	13,892,218	10,860,980	12,586,55
North Carolina	101,180	202,416	(2)	(2)	(2)	(2)
Ohio	14,241,690	11,789,747	12,482,760	9,285,089	8,886,640	5,958,26
Oklahoma	2,074,990	1,552,178	1,942,750	1,505,716	1,534,410	1,203,15
Oregon	23,800	58,442	(2)	(2)	(2)	(2)
Pennsylvania..	14,525,080	14,024,287	12,100,700	12,375,067	8,350,060	8,552,69
Puerto Rico ..	55,960	90,675	37,760	85,324	31,450	55,5
Rhode Island..	380	1,171	300	758	60	1
South Dakota..	40,590	55,513	36,770	39,705	39,370	37,3
Tennessee	2,249,440	2,304,002	1,640,530	1,688,763	1,462,600	1,535,6
Texas	3,238,760	2,390,235	2,007,160	1,646,694	1,125,790	951,7
Utah	203,530	224,097	631,420	368,992	164,450	173,3
Vermont	42,360	129,251	39,360	114,053	39,660	115,2
Virginia	2,516,120	2,481,192	2,925,560	2,868,938	2,201,430	2,115,1
Washington ...	75,440	129,423	119,140	165,809	131,600	213,9
West Virginia.	3,301,160	2,978,873	3,008,880	2,653,954	2,017,570	1,768,2
Wisconsin	3,441,070	3,882,645	2,712,640	2,677,898	2,231,190	2,142,9
Wyoming	322,260	473,678	207,380	343,637	166,110	232,8
Undistributed.	304,020	305,681	304,790	426,566	770,060	1,097,3
Total ...	100,686,960	113,906,071	88,741,440	100,002,114	66,751,040	71,875,

1 Limestone used in cement and lime manufacture not included.

2 Included under "Undistributed."

BRANCHES OF THE INDUSTRY

The limestone industry is divided into two distinct branches - dimension stone and crushed stone. The outstanding distinction is that dimension stone is prepared for use in blocks of definite shapes and often in specified sizes. Rough building stone may consist of quite irregular blocks, but usually at least one good face is demanded. On the other hand, crushed or broken stone consists of irregular fragments.

The two branches have little in common. In quarrying dimension stone, explosives are employed very sparingly because the integrity of blocks must be preserved, but heavy charges of dynamite are used in the crushed-stone quarry to blow the rock into fragments. All subsequent methods and equipment for preparing the products for market are entirely dissimilar. Marketing problems are necessarily diverse.

The crushed and pulverized limestone industries are again subdivided into three main branches, one including stone sold or used in its natural state except for crushing, grinding, and sizing; and the other two involving the manufacture of cement and lime - the important primary products manufactured in conjunction with quarrying operations. The amount of limestone used for all purposes for a series of years is shown in table 2. The first item of this table including all limestone sold or used except that employed in cement and lime manufacture is subdivided by uses for a period of 3 years in table 3.

Detailed statistics of the limestone industry and also of the lime and cement industries are published annually by the Bureau of Mines. These reports may be procured from the Superintendent of Documents, Washington, D.C.

Table 2.- Limestone used for all purposes in the United States, 1927-1931, in short tons
(Quantities approximate)

Use	1927	1928	1929	1930	1931
Limestone (as given in table 3)	99,662,270	96,864,650	100,686,960	88,741,440	66,751,040
Limestone used in cement (including "cement rock") ..	44,195,000	45,012,000	43,612,000	40,841,000	31,736,000
Limestone used for lime manufacture.	8,830,000	8,920,000	8,540,000	6,780,000	5,420,000
Total	152,687,270	150,796,650	152,838,960	136,362,440	103,907,040

Table 3.- Limestone sold or used by producers in the United States, 1929-1931, by uses[1]

(Quantities approximate)

	1929		1930		1931	
Use	Short tons	Value	Short tons	Value	Short tons	Value
Building stone 2/..	1,312,820 (17,864,700 cu. ft.)	$20,649,257	1,152,780 (15,682,720 cu. ft.)	$18,535,293	872,630 (11,706,840 cu. ft.)	$10,858,6
Curbing, flagging, and paving	37,940 (471,880 cu. ft.)	158,266	27,760 (346,040 cu. ft.)	137,801	15,220 (166,260 cu. ft.)	85,175
Rubble	352,480	693,678	756,470	625,100	229,510	296,433
Riprap	2,080,580	2,655,374	2,918,110	3,318,084	2,508,160	2,763,571
Crushed stone	61,465,200	58,934,450	56,775,060	54,154,317	46,601,900	42,752,256
Fluxing stone	24,337,280	17,994,110	17,201,350	12,312,602	9,674,800	7,160,530
Sugar factories ...	487,990	874,909	414,340	733,359	433,640	748,632
Glass factories ...	257,370	455,367	224,180	349,771	159,220	244,456
Paper mills	273,880	456,251	248,790	377,059	194,310	268,140
Agriculture	2,654,580	3,764,775	2,542,100	3,309,329	1,421,050	2,117,141
Alkali works	5,004,930	3,234,457	4,436,160	2,759,245	3,340,290	2,186,422
Asphalt filler ...	344,880	1,165,538	430,290	1,122,939	247,450	778,045
Calcium carbide works	339,510	236,412	364,750	275,296	164,180	96,153
Carbonic acid works	4,560	10,708	2,290	5,700	2,670	5,605
Coal-mine dusting ..	34,650	121,712	47,750	132,385	38,040	117,715
Fertilizer filling ..	3,910	8,656	12,240	21,194	(3)	(3)
Filter beds	72,870	63,277	30,860	23,633	56,100	53,193
Magnesia works (dolomite)	84,750	129,383	111,740	189,219	80,820	122,625
Mineral food	25,270	96,009	30,350	96,216	21,880	93,31
Mineral (rock) wool	83,920	92,092	64,850	70,988	73,640	67,3
Poultry grit	34,600	221,610	45,920	197,327	31,320	159,5
Refractory stone (dolomite).	516,400	461,444	453,350	356,025	268,500	183,03
Road base .	494,250	213,802	139,030	34,106	(3)	(3)
Roofing gravel ...	4,950	10,968	1,740	5,154	(3)	(3)
Stucco, terrazzo, and artificial stone	85,540	292,313	59,570	208,990	45,760	122,1
Whiting substitute	125,430	626,692	119,350	492,894	73,420	408,8
Other uses[4]	166,420	284,561	310,260	159,488	176,530	166,1
	100,686,960	113,906,071	88,741,440	100,002,114	66,751,040	71,875,5

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1 Limestone used in cement and lime manufacture not included.

2 Figures for building stone include small amounts of monumental stone.

3 Included under other uses.

4 Includes stone for ammonia, baking powder, dye works, lime burners, nitrates, phosphates, powder, purification of copper, soap, sulphuric acid, and uses not specified.

DIMENSION STONE

While innumerable limestone occurrences are to be found throughout the country, only a few of them consist of rock that will satisfy the exacting requirements of dimension stone. Deposits with irregular or closely spaced joints are not suitable, as only large blocks free from cracks or lines of weakness are in general demand. Limestones display great variation in physical properties such as texture, porosity, hardness, strength, and color; and upon these properties depend their adaptability and value as dimension stones. Only those limestones that are compact, of easy workability, uniform texture, and attractive color are worthy of consideration for this use. Chemical composition is of little significance.

Dimension stone is used principally for building purposes. It may be used for entire exteriors or in conjunction with brick or other building materials. It is also used widely for columns and for interior structural and decorative purposes. The district surrounding Bedford and Bloomington, Ind., produces more than 80 percent of all the building limestone quarried in the United States. It is produced also in Alabama, Kentucky, Minnesota, Texas, Colorado, and Florida and in small amount in a few other States. A discussion of the occurrence, properties, quarrying, milling, and manufacture of dimension limestone will appear in a forthcoming report.

CRUSHED AND PULVERIZED LIMESTONE

Extent of the Industry

Crushed and pulverized limestone found limited use many years ago, but the intensive building activity, public works and highway construction, and industrial development that have characterized recent years have opened up many new and extensive channels of use for this most adaptable of all rocks. The enormous tonnage of crushed and broken limestone consumed in industry is shown in table 4.

Table 4.- Crushed and broken limestone sold or used by producers in the United States, 1921-1931[1]

Year	Short tons
1921	74,358,800
1922	95,184,780
1923	118,342,190
1924	120,506,160
1925	134,220,530
1926	141,321,640
1927	151,163,700
1928	149,025,390
1929	151,135,720
1930	134,425,430
1931	102,789,680

[1] Includes stone used for cement and lime manufacture.

Uses

Beginning with the fourth item, riprap, of table 3, the principal uses of crushed, broken, or pulverized limestone are enumerated, together with the tonnage and value for each over a period of 3 years. These figures indicate the relative importance of the various uses as market outlets for limestone. The specific requirements for each purpose are covered in following pages.

For many of the uses of stone in crushed form, physical properties are of primary importance; for others, certain chemical compositions are requisite. Limestone possesses the physical qualities that make it adaptable for practically all the uses for which any crushed stone may be employed and also has active chemical properties that make it not only useful but absolutely essential to a great many industries.

Uses for Which Physical Properties are Most Important

Concrete Aggregate.- A vast tonnage of limestone is used as aggregate for concrete, in which form it is consumed chiefly in highway construction and in the building trades.

While consumers differ as to the requisite qualities of material for aggregate, generally it should consist of clean, hard, strong, durable, uncoated fragments free from injurious amounts of soft, friable, thin, elongated, or laminated pieces. Alkalies and organic matter are usually undesirable. Soluble sulphides are objectionable because they oxidize; the sulphuric acid formed attacks any calcareous material or lime in the cement and forms gypsum, which expands during crystallization and disrupts concrete.

Various tests are made to ascertain the fitness of limestones. They include the Deval abrasion test, the Dory hardness test, the Page impact test, and the ordinary methods of crushing-strength tests. For determining soundness the more important are the freezing and thawing, the sodium-sulphate, the sodium chloride, and the alkali tests; each involves the freezing or crystallization of a substance in the pores or cracks, which results in a heavy interior strain.

State highway officials are recognizing the need of more uniform specifications, and recently have instituted a set of tentative standards[4] for material to be used in macadam and concrete highways.

Also, much study is being devoted to the proper sizing of aggregate and the proper proportioning of the various sizes to obtain maximum strength and durability with a minimum of cement. It is desirable to use a combination of different sizes that will give the lowest percentage of voids.

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[4] Tentative Standard Specifications for Highway Materials of the American Association of State Highway Officials: Washington, 1929, 56 pp.

Road Stone.- Stone of various sizes is used in the construction of bituminous and macadam roads. Material under one fourth inch is classed as fine screenings and is used principally for waterbound macadam. Coarser screenings, up to one half inch, serve as fine aggregate for bituminous concrete. Sizes between one fourth and three fourths inch are dustless screenings or chips for surface treatment of bituminous roads. Coarse chips, between three-fourths and 1½ inches, are used for bituminous macadam. Sizes from 1¼ to 2½ inches are suitable for the wearing course of both waterbound or bituminous macadam. Rock between 2½ and 3½ inches constitutes the base course of highways.

The requisite qualities of road stone are similar to those of aggregate except that resistance to abrasion is of primary importance. A soft rock disintegrates under traffic, and a laminated rock, even if fairly hard, breaks into flat or elongated pieces which will not compact solidly. Rock of low porosity is desirable, as otherwise water may penetrate and soften the structure of the road. Road stone should break into sharply angular, chunky fragments which when properly graded as to size will interlock and press firmly into the surface of the road.

Various standard methods of testing, sampling, and mechanically analyzing road materials are given in the American Society for Testing Materials Standards, 1927, Part 2.

Railroad Ballast.- Many thousand tons of limestone are consumed by railroad companies for the maintenance of their road beds. A minimum of three fourths inch and a maximum of 2½ inches for ballast sizes has been fixed. The requirements as to quality are generally the same as for aggregate and road stone.

Asphalt Filler.- Limestone dust, approximately 80 percent of which will pass a 200-mesh screen, is used as a filler in road asphalt-surface mixtures. Many thousand tons are consumed annually in this way. For the most part it is regarded as a by-product outlet, though the preparation of asphalt filler is an appreciable part of the business of some quarrying companies.

Riprap.- Riprap consists of heavy, irregular rock used chiefly for river and harbor work, such as spillways at dams, shore protection, and docks. It is a low-priced product and is usually procured from near-by quarries. Any type of dense, sound limestone may be used, there being no general specifications.

Coal-Mine Dusting.- Several hundred operators of bituminous coal mines now employ fine incombustible dusts for distribution throughout their mines as a means of preventing or checking coal-dust explosions. Limestone dust is particularly satisfactory for this purpose because it is essentially carbonate of lime, which is not injurious to the lungs, and because being white the proportion of inert material present can be readily estimated. However, limestone with high silica content is not desirable for dusting. Screen-size specifications are not exacting. Those approved by this Bureau require that 100 percent shall pass through a 20-mesh screen, and 50 percent through a 200-mesh screen.

As the material commands a low price, it is usually furnished by quarries situated near the coal mines. Approximately 60,000 to 70,000 tons of pulverized limestone are consumed annually in this way.

Sewage Filter Beds.- Crushed limestone has been found satisfactory as sewage filter beds. High-calcium or dolomitic limestone may be used, and siliceous impurities are not objectionable if they are fine grained and evenly distributed. Certain other impurities, notably pyrite, marcasite, and clay, are to be avoided. The rock should be strong and compact with pore space evenly distributed, and the fragments should be sufficiently rough to provide anchorage for bacteria. Fines and dirt should be screened out.

Stucco and Terrazzo.- Dense compact limestones of attractive colors may be crushed into small fragments for terrazzo floors. Similar material reasonably impervious to moisture finds some use in stucco and pebble-dash work.

Poultry Grit.- Limestone crushed to granular form and screened to uniform sizes is sold for poultry grit. Almost any type of limestone may be so used.

Sand.- Limestone crushed to the size of sand grains when carefully washed and graded may be substituted for silica sand in mortar, wall plaster, and concrete. Mortar tests as reported by Kreige[5] showed strengths considerably in excess of those obtained with standard silica sands. A large tonnage of limestone sand has also been used in concrete highway construction in the Middle West.

Roofing Gravel.- Screened limestone chips are sold as gravel to be used with tar for coating flat roofs.

Yard and Playground Surfacing.- Screenings without a binder afford good surfaces for school yards, playgrounds, walkways, station platforms, and tennis courts.

Concrete-Block Manufacture.- Limestone screenings are used as aggregate in the manufacture of concrete blocks, and limestone chips may be embedded in the surface to make the blocks resemble cut stone.

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[5] Kreige, Herbert F., Washed Limestone Sand: Pit and Quarry, vol. 17, No. 11, 1929, pp. 64-66.

Chalk, Whiting, and Whiting Substitute.- Chalk is a noncrystalline, soft, friable, fine-grained, light-colored type of limestone. The distinguishing physical characteristics of true chalk never have been fully defined; probably its noncrystalline and colloidal properties are most important. Whiting is a pulverized, purified, and carefully sized chalk. Whiting substitutes consist of finely ground limestone or dolomite, ground marble, white marl, and chemically precipitated calcium carbonate. Very little true chalk has been produced in the United States.

True whiting is preferred for calcimine and cold-water paints and in the manufacture of putty. Other uses of whiting are as a ceramic raw material and as a filler in numerous products, such as rubber, paint, paper, oilcloth, window shades, and linoleum. The uses are discussed in more detail in another publication of the Bureau.[6]

Uses for Which Chemical Properties are Most Important

The importance of the chemical composition of limestone for certain uses is not always to be interpreted as a demand for pure calcium carbonate. The manufacture of cement, for example, calls primarily for a proper balance between the chemical constituents, and suitable limestone may be quite impure. Chemical purity, however, is demanded for some purposes.

Cement Manufacture.- Limestone is the chief raw material of cement. While pure limestone is not required, constancy in chemical composition is desired. The general requirements are that (1) rock should be free of concretions of iron mineral; (2) the silica and alumina contents should be sufficiently low and in such proportions that they will not interfere with the desired silica-alumina ratio in the finished product; (3) the magnesium content should be low enough that the finished product will not contain more than 5 percent magnesia (MgO); (4) the content of iron should be sufficiently low that the ferric oxide content of the cement does not exceed 4 percent; (5) the sulphur content should be low.

Cement rock is simply an argillaceous limestone which contains enough clay as it occurs in nature to adapt it for the manufacture of cement. Sometimes it may be necessary to adjust its composition by adding small amounts of either high-calcium limestone or clay. The cement industry consumes many millions of tons of limestone every year, but the successful operation of a cement plant depends upon fuel supplies, transportation facilities, market demands, production costs, and competitive conditions, as well as upon suitable raw materials.

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[6] Bowles, Oliver, Chalk, Whiting, and Whiting Substitute: Inf. Circ. 6482, Bureau of Mines, 1931, 13 pp.

Lime Manufacture.- Between 8,500,000 and 9,000,000 tons of limestone are used annually in the United States for lime manufacture. For such use stone must conform with rather rigid physical and chemical requirements. Exceptionally pure stone, total carbonates ranging from 97 to 99 percent, is generally used because practically all impurities remain in the lime that results from calcination. The most common impurities are silica, alumina, iron, and sulphur. The stone should be sound and compact because porous and friable types break down during calcination, and the large quantity of fines resulting from quarrying can not be used in shaft kilns. Both high-calcium and high-magnesium limestones, or dolomites, are used.

Lime enters three important fields of utilization - the chemical industries, the building industries, and agriculture. High-calcium limes are used chiefly for mortars and chemical purposes, and magnesian limes for finishing plasters. Both high-calcium and high-magnesium limes are used for soil treatment, and for this use a larger percentage of impurity is tolerated than for most of the other applications.

Furnace Flux.- Normally from 20,000,000 to 24,000,000 tons of limestone are used annually as fluxing material in the iron furnaces of the United States. As the chief purpose of flux is to remove silica and alumina from ores, it is evident that limestone employed for this purpose should have a small content of these elements. If an impure stone is used, part of the carbonate content is absorbed in fluxing off the foreign elements in the stone, which reduces the amount available for removing impurities of the ore. "Available carbonate" is a term applied to the percentage of calcium and magnesium carbonates available for fluxing ore after a sufficient percentage has been deducted to neutralize impurities in the stone itself. While a low content of impurities is desirable, conditions greatly influence the use of pure and impure stone. Silica and alumina in a fluxing stone do no real harm in a blast furnace; they merely make the stone less effective, increase slag volume and fuel consumption, and slow up production to a limited extent. If the price differential between an impure stone and one of high chemical purity is sufficient to offset these disadvantages, the lower-priced product may be more economical to use. Generally the presence of magnesium in the stone is not regarded as objectionable. Sulphur in fluxing stone should not exceed 0.5 percent. The upper limit of phosphorus for Bessemer iron is placed at 0.01 percent and for non-Bessemer iron at 0.1 percent.

A relatively small tonnage of limestone is used in the manufacture of basic open-hearth steel. Purer stone is required for making steel than for blast-furnace work; the silica content is usually limited to 1 percent, and the alumina content to 1.5 percent. As one of the chief purposes is to remove phosphorus, and as magnesium is a poor phosphorus remover, the maximum permissible content of MgO is usually 5 percent. More complete information on both production and use of fluxing stone is given in a Bureau report.[7]

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[7] Bowles, Oliver, Metallurgical Limestone: Bull. 299, Bureau of Mines, 1929, 40 pp.

Agricultural Uses.- Limestone finds important applications in agriculture as a fertilizer, soil conditioner, and as a corrective for soil acidity. Pure limestone is desirable though not essential, for while impurities lessen the percentage of calcium or magnesium available for improving the soil, they are not injurious to plant growth. Therefore, local impure limestone may be more economical than higher-grade material that must bear a relatively heavy transportation charge. There is some difference of opinion regarding the suitability of dolomitic limestone, but most authorities agree that magnesium is of equal value with calcium and that the value of stone for agricultural purposes may be measured by the percentage of total carbonates present.

A small amount of limestone is used with commercial fertilizers as a diluting material or filler.

Stock Food.- Pulverized limestone is added to stock food as a bone builder.

Alkali Manufacture.- The manufacture of sodium carbonate (soda ash) consumes from 4,000,000 to 5,000,000 tons of limestone a year. The Leblanc process (almost obsolete) involves a reaction between limestone, sodium sulphate, and carbon to form the desired sodium carbonate. A furnace charge consists of 100 pounds of salt cake (sodium sulphate), 100 pounds of limestone, and 50 pounds of coal-dust. The magnesia and silica content of the limestone should be low, or loss will ensue through the formation of insoluble residues.

For the ammonia or Solvay process, which is generally used, the principal reaction is in a brine. Carbon dioxide and lime are obtained by calcination of limestone in special continuous kilns. Chemically pure limestone, though not essential, is desirable. About 1½ tons of limestone, preferably in pieces to 6 inches in size, is used per ton of soda ash produced.

Calcium Carbide.- Calcium carbide is manufactured by fusing an intimate mixture of powdered lime or limestone and coke in an electric furnace. About tons of limestone is required for each ton of carbide made. Very pure stone s required. The content of phosphorus should be less than 0.01 percent; agnesia, less than 2 percent; and silica, less than 3 percent.

Sugar.- Limestone is used in large quantities in refining beet sugar. t is calcined into lime and used in milk-of-lime suspensions to precipitate mpurities from the juices, or, in the Steffen process, to precipitate sugar rom impure solutions. Calcination is preferably done at the refinery as the carbon dioxide is recovered for use in subsequent treatment of juices. The ime requirement is about 2½ percent of the weight of beets.

Limestone generally used is in sizes from 2 to 6 inches and averages 97 to 99 percent calcium carbonate. Silica is detrimental, and iron oxide affects the color of the sugar. According to specifications[8] limestone (calcined before analysis) for the Steffen process should contain at least 90 percent of sugar-soluble lime and not more than 3 percent of magnesium oxide.

Glass.- Either lime or limestone is used in the manufacture of glass. Limestone of uniform grade is required because of the rigid control necessary in composition of the batch. The iron content should be low because of its coloring effect; for optical glass it must be practically zero. Silica in moderate amounts is not detrimental, but the sulphur and phosphorus content should be low. Combined calcium and magnesium oxide requirements (on a calcined basis) are about as follows: At least 89 percent for bottle glass, 91 percent for sheet glass, 93 percent for blown glass, 96 percent for rolled glass, and 99 percent for optical glass.

Rubber.- Limestone or its products are used in two ways in rubber manufacture - as whiting and as hydrated lime. The whiting acts as a filler and also assists in controlling hardness and elasticity in building compounds. Powdered chalk is used in the manufacture of rubber cement.

Paper.- The acid liquor used in one method of manufacturing paper is obtained by treating either milk of lime or wet limestone with sulphur dioxide. Dolomite or high-magnesian limestone is preferred for preparing the lime, and should be pure enough to give a product containing not more than 3 percent total iron oxide, alumina, silica, or other insoluble impurities.

Another method of obtaining acid liquor is by the Jennsen tower system, whereby sulphur gases pass through a tower packed with limestone. Stone for this purpose should have not more than 2½ percent of magnesium carbonates or other impurities, and a calcium carbonate content of at least 95 percent is recommended. Medium-grained stone in fragments from 8 to 14 inches is used.

Carbon Dioxide.- During recent years the use of carbon dioxide has increased greatly, chiefly because of its employment in solid form as a refrigerant. Dolomite is used to some extent as a source.

Mineral Wool.- The name "mineral wool" or "rock wool" is applied to fine interlaced threads of calcium silicate used chiefly in heat insulation. It is made by melting argillaceous limestone in a cupola furnace and blowing the slag which is formed into fine threads by means of a steam jet.

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[8] U. S. Bureau of Standards, Recommended Specifications for Limestone, Quicklime, Lime Powder, and Hydrated Lime for Use in the Manufacture of Sugar: Circular 206, 1925, 6 pp.

Uses of Dolomite and High-Magnesian Limestone

Some of the uses for which a magnesium content is essential or preferred are covered in preceding paragraphs. There are in addition several special uses.

Refractories.- Dolomite and high-magnesian limestone are used extensively as refractory linings in metallurgical furnaces. The dolomite may be dead-burned or used in the raw state. A dead-burned product is made by calcining the raw material at a temperature of about 1500° C.

Technical Carbonate.- Dolomite is used in large quantities for the manufacture of basic magnesium carbonate, which is employed chiefly for pipe and boiler covering.

Further details on the uses of dolomite are given in a recent Bureau report.[9]

Quarry Methods

Prospecting.- Development work should not be started on a deposit without reasonable assurance of an available mass of rock sufficiently high in quality and abundant in supply for profitable exploitation. If the rock appears in bare outcrop, usually a rough estimate as to its quality and extent can easily be made. Limestones are as a rule fairly constant in composition throughout the same bed or zone of deposition; the greatest variations are found in passing from one bed to another. Therefore, all beds that may be included in a quarry are usually sampled. If a cross section is not available in nature, test holes are drilled at such intervals as will supply adequate data covering the whole area under consideration. Churn drills are usually employed, and samples of the cuttings for analysis are taken at regular intervals. No definite rules can be given either for the position or arrangement of holes. In flat-lying beds of uniform thickness and fairly constant composition they may be spaced at wide intervals - 100,500, or even 1,000 feet; where beds are folded or tilted or where changes in composition or structure occur within short distances, they should be more closely spaced. Accurate permanent records of all drilling are highly desirable. The direct cost of sinking churn-drill holes 5½ to 6 inches in diameter in limestone varies from 20 to 60 cents a foot.

When the extent of a deposit is known the approximate tonnage may easily be determined. Limestone weighs on an average about 160 pounds a cubic foot. To determine the approximate number of short tons available in a deposit, the length, width, and depth in feet may be multiplied; this product is multiplied by the average weight per cubic foot, 160 pounds, and divided by 2,000.

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[9] Hatmaker, Paul, Utilization of Dolomite and High-Magnesium Limestone: Inf. Circ. 6524, Bureau of Mines, 1931, 18 pp.

More complete data on quarry methods are given in other reports of the Bureau.[10]

Generally it is deemed unwise to expend money on quarries, crushers, and screening plants unless a reserve of good rock sufficient for at least 20 years' operation is assured.

Stripping.- Stripping is the process of removing the overburden of clay, gravel, or sand from the rock surface. The depth of overburden varies from a few inches to 10, 20, 30, or even 40 or more feet. Likewise, the nature of the materials composing it is variable. It may be easily disintegrated loam, sticky plastic clay, sand, gravel, boulders, or a hardpan that may require blasting. The presence of erosion cavities in the limestone surface may make stripping difficult. Many different stripping processes are employed. The more important of them are the hydraulic method, the drag-line scraper, power shovel, clamshell bucket worked from a derrick arm, scrapers hauled by horses or mules, or hand methods with picks and shovels. Costs of power-shovel stripping, the most common method, vary under average conditions from 30 to 50 cents a cubic yard. A detailed discussion of stripping is given in a former report.[11]

Plan.- The method of quarrying a deposit depends on thickness and dip of beds. If the strata are horizontal or inclined at low angles, open-pit quarries are developed except where the overburden is so heavy that underground work is better. When such beds are thin, the pit must be enlarged laterally; when thick, deeper and narrower quarries are made.

When beds are tilted at steep angles and are many feet thick, an open quarry may be worked to considerable depth, but removal of waste to avoid a dangerous overhang involves ever-increasing expense as the floor is deepened. When tilted beds are thin, any lateral extension must be in the direction of the strike or outcrop. The narrowness of the working face of a thin bed cramps operations and makes it difficult to obtain large daily tonnages, but quarrying at several levels partly overcomes this condition. Underground methods are commonly followed where the overburden is excessive or where comparatively narrow beds stand at steep angles.

Drilling.- The churn drill, commonly called the "well drill," is the typ most widely used for primary drilling, although piston drills are also used for this purpose. Hand-manipulated compressed-air hammer drills are so employed to some extent, but they are used chiefly in secondary drilling in preparing pop shots to break up larger fragments.

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[10] Bowles, Oliver, Rock Quarrying for Cement Manufacture: Bull. 160, Bureau of Mines, 1918, 160 pp.
Bowles, Oliver, and Myers, W. M., Quarry Problems in the Lime Industry: Bull. 269, Bureau of Mines, 1927, 97 pp.

[11] Bowles, Oliver, and Myers, W. M., Quarry Problems in the Lime Industry: Bull. 269, Bureau of Mines, 1927, pp. 15-26.

As the purpose of drilling is to obtain space for explosives, the only fair method of comparing costs is to consider drilling not in terms of cost per foot but rather on the basis of the volume of the hole obtained. Churn drills are usually preferred because under average conditions when compared with the smaller drills they provide larger space for explosives at lower cost. The advantage probably lies with small drills for shallow benches and with churn drills for high benches.

A comparatively large space for explosives is sometimes provided by "springing" small drill holes. The process consists of discharging in the bottom of the hole a succession of small explosive charges, thereby pulverizing and removing the rock to form a cavity.

Blasting.- Heavy blasting to break rock from the parent ledge is known as primary blasting. When a primary shot is not sufficient to break the rock to sizes small enough for loading, secondary blasting may be employed. It is generally considered that heavy blasts in churn-drill holes are the most effective, but advocates of small-hole blasting think that a more general distribution of the explosive throughout the rock mass breaks it more completely, and it requires less block-hole shooting than does churn-drill blasting. Undoubtedly different results are obtained in different types of rock. Blasting in deep churn-drill holes is the method commonly employed. The charge in each hole should be regulated according to the estimated tonnage of rock to be moved. In average practice a pound of 40 percent ammonia dynamite shatters 3 to 6 tons of rock, the amount depending on the toughness of the rock.

For practically all primary shots explosives are fired simultaneously. When electric detonators are used the drill holes are connected either in series or in parallel or multiple. Another way of firing is to use a detonating fuse consisting of a lead tube filled with trinitrotoluene. A main line connecting the branches from each hole is attached to the detonator, and all charges are fired at practically the same time.

A method adaptable for blasting a high face when the strata are irregular is to fire charges in small tunnels driven into the quarry face at the floor.

To promote blasting efficiency many quarry superintendents keep accurate records which show for each shot the number and depth of holes, spacing, burden, kind and weight of explosive in each hole, tonnage of rock moved, and condition of fragmentation.

There are two common methods of secondary blasting. "Mud-capping" consists of placing a stick of dynamite with attached fuse on the surface of the rock to be broken and covering the dynamite with clay which confines the explosion and directs it toward the rock. "Blockholing" is much more effective. Holes several inches deep are drilled, and a stick, or part of a stick, of dynamite with a fuse attached is placed in each one. Rock-dust or clay is used for stemming. A number of blasts are discharged in rapid succession.

Ammonia dynamite is most commonly used in quarry work. Gelatin dynamite should be used in wet holes. Liquid oxygen (commonly designated "L.O.X.") used to some extent as a substitute for dynamite is quite effective, but its use is rarely advised except where quarries are located near a liquid-oxygen manufacturing plant or companies are large enough to justify the manufacture of their own supplies.

Loading.- Loading rock into cars is the largest single item of quarry expense. It is done by hand at many quarries supplying lime plants or producing flux for furnaces because pure stone has to be provided and this method affords a means of selective loading with rejection of siliceous or otherwise impure fragments.

In quarries producing aggregate, road stone, or ballast, power shovels are generally used. For a daily output of 150 to 300 tons of rock small tractor shovels with $\frac{3}{4}$- to $1\frac{1}{4}$-yard dippers are suitable, but shovels with dippers capable of handling 5 to 10 tons are employed in the larger quarries. Records obtained from a number of quarries a few years ago show an average daily output of 112 tons per man (pitmen and shovelmen only) by power shovel as contrasted with 16 tons per hand-loader. Very little secondary blasting is necessary when power shovels load the rock, whereas not only blockholing but a great deal of laborious sledging must be done when it is removed by hand. However, the mechanical method requires expensive accessory crushing and screening equipment, and the large investment thus involved may make it more profitable to load by hand at small quarries.

Haulage.- Haulage involves the motive power and equipment required to convey rock from the loading place to some point outside the quarry where it is transshipped, crushed, or otherwise treated.

The arrangement of tracks depends on the loading method and the size and shape of the quarry opening. When loading is done by hand it is desirable to have many working places, each with independent trackage from the main line. For power-shovel loading two systems are followed. When the face is wide, the track parallels it, and a succession of cars are loaded; when the face is narrow, the track runs directly toward it and ends in a Y. Tracks from pit quarries may be inclined; many are so steep that cables are used. Tracks from shelf quarries may be level or moderately graded. The gage of tracks ranges from 24 to 42 inches. Low cars of 2- to $2\frac{1}{2}$-ton capacity are popular in small quarries, but larger and stronger cars are used for power-shovel loading. Side-dump cars are most commonly used.

Various types of motive power are used. Careful adjustment of grades makes car movement largely automatic. On a gentle grade loaded cars may proceed by gravity from the face; the empties may be returned by horses or mules. Animal power has been preferred for short hauls, but smaller types of electric or gasoline locomotives are replacing it. When the haulage distance exceeds 500 feet, locomotives are generally employed, and they may haul as many as 20 cars. Cable and drum haulage is commonly employed on inclines. Trucks are another means of conveyance.

Underground Mining

The chief factors that make underground mining of limestone advantageous at times are (1) a heavy overburden of soil or inferior rock blanketing a flat-lying deposit of good stone; (2) an inclination of beds of serviceable material that demands too great an extension of the pit along the strike or outcrop and results in an increasing overburden as the pit is enlarged in the direction of the dip; and (3) the necessity for working at increasing depths as surface deposits are exhausted. Crushed limestone is too low-priced a product to justify the expense of timbering mines except possibly in shafts or entries; hence, mining is successful only when the rock is strong and massive enough to constitute the roofs and supporting pillars.

The principal advantages of underground work are avoidance of stripping expense and soil contamination, and protection of laborers from inclement weather. However, drilling and blasting are more expensive than in open-pit work, the proportion of fines is increased, and from 20 to 25 percent of the stone must be left as pillars. In making a choice between underground and open-pit methods each operation must be considered on its own merits.

Mining methods are fully described by Thoenen in a publication of this Bureau.[12]

Preparation of Materials

Crushing.- Four main types of crushers are in general use - the gyratory crusher, the jaw crusher, double rolls, and single rolls; cone and disk crushers are also used. The size of a crusher should be governed by the size of the blocks to be crushed and by the daily output desired. The first cost and power charge of large crushers are high, but maintenance expense is usually low, and no delays are caused by jammed blocks.

Screening.- Crushed stone is assorted according to size by some type of screen. For separation of the larger sizes an inclined railroad rail or bar grizzly with 3½- to 5-inch spacing is sometimes used. The rotary screen or trommel has been most widely employed. More recently, however, for coarser sizing or scalping, rotary disks such as the cataract grizzly or the multiroll sizer have been adopted. The advantages claimed are long wear, absence of vibration, and minimum grinding and breaking, as there is no cascading action. The finer sizes are usually graded by vibrating screens.

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[12] Thoenen, J. R., Underground Limestone Mining: Bull. 262, Bureau of Mines, 1926, pp. 33-80.

Washing.- Demand for clean stone with a minimum of fines has led to the addition of washing equipment at many quarries. Washing is particularly desirable at quarries where clay seams occur. It is generally accomplished by directing water on the stone as it cascades in a trommel or passes over rotary disks or vibrating screens.

Elevating and Conveying.- When a crushing plant is located on the quarry floor, the stone may be elevated to screens or to storage by bucket elevators or belt conveyors. Cascading from high elevations is to be avoided because it produces fines, particularly if the limestone is soft.

Fine Grinding.- Limestone is reduced to ground form usually by dry-grinding processes. When prepared in this manner the moisture content must be low, and hence the stone is usually passed through rotary dryers. Roller mills of various types, also impact, beater, or swinging-hammer mills are used. For very fine-grained products ball or pebble mills are preferable.

Classification of the smaller sizes is accomplished by air separation, and of the coarser material by vibrating screens.

Grinding efficiency is increased by the removal of material from the system as soon as it is ground. In closed-circuit grinding the coarser particles are returned to the system for further reduction. Wet processes are sometimes preferred for the preparation of whiting or marble flour. Size classification is then accomplished by water settlement.

Operating Costs

Average costs are difficult to estimate because conditions are so variable in different quarries that both individual items and total costs are quite diverse. Thoenen[13] estimated a cost of 67 cents a ton as an average for 30 open-pit limestone quarries in various parts of the country. For an average quarry operating on a large scale this total might be distributed as follows: Stripping, 6; drilling, 9.5; explosives, 7.5; loading (hand), 22; mucking, 6; haulage, 5; repairs, taxes, etc., 5.5; interest and amortization, 5.5. If a power shovel is used, the direct loading cost would be much less than 22 cents, but with interest on investment, together with additional crushing expense, the total would probably differ little from the hand-loading cost. A cost analysis by Thoenen[14] of 110 limestone quarries grouped according to size and equipment shows direct quarrying and crushing costs ranging from 35 to 95 cents a ton.

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[13] Thoenen, J. R., Work cited, p. 94.

[14] Thoenen, J. R., Study of Quarry Costs: Rept. of Investigations 2911, Bureau of Mines, 1929, p. 2.

Markets

Crushed stone is a low-priced product and as the transportation charge is usually a large part of the delivered price, it has a relatively limited market range. Profitable operation depends largely on the extent of local markets. Producers are most concerned about steady market requirements of near-by builders, contractors, State highway departments and other users. A wise operator gages his plant capacity by the normal demand but is prepared to profit by any extraordinary market opportunities.

Demand is influenced by availability and cost of other materials and by competition of concrete with brick, stone, or other building products.

Prices

Prices of crushed limestone are subject to local conditions of production, cost, and competition and vary widely even within restricted areas; therefore, the determination of selling price is a problem for each producer. About 50 quotations representing the chief centers usually appear in the market columns. The average value of the 1931 production as reported to the Bureau of Mines was 92 cents a ton f.o.b. plant - the lowest average since the World War. The highest average figure during the same period was $1.19 a ton in 1920.

Royalties

Many crushed-stone producers operate in deposits which they do not own. It is customary in such instances to pay the owner of the property a royalty of so much per ton of crushed stone sold. Royalties vary from 1 to 10 cents a ton depending on local conditions. The lower figures usually prevail where production is large, but sales value per ton, production cost, or competition may influence the amount. A minimum average daily or monthly production is usually a condition of a royalty agreement.

Capital Requirements

A prospective operator desires to know how much capical he must have in order to establish a crushed-stone industry. The most reasonable basis for expressing investment is the capital required per annual ton of production. Thus, if $1,000,000 is needed to build a plant capable of producing 1,000,000 tons a year, the investment is $1 an annual ton. Capital investment, like costs, varies greatly from plant to plant, but average figures are at least indicateive of what one may expect.

A detailed study[15] of 64 crushed-stone plants in the United States shows an average capital investment of $1.25 an annual ton of average production over a 2-year period. This figure is based on depleted values representing actual replacement values of the properties. Therefore, a prospective producer who is just beginning operation must estimate his initial investment at a somewhat higher rate than the figure given above. Of the total capital requirement land and mineral constitutes about 15 percent; and plant and equipment, about 85 percent.

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[15] Bowles, Oliver, Economics of Crushed-Stone Production: Econ. Paper 12, Bureau of Mines, 1931, p. 53.